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ScienceDirect
Procedia Engineering 80 (2014) 258 – 271
Procedia Engineering
www.elsevier.com/locate/procedia

3rd International Symposium on Aircraft Airworthiness, ISAA 2013

A modeling method on aircraft engine based on the Component Method of secondary air system

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Abstract

The dynamic characteristic of transient secondary air system has the significance to ensure the airworthiness safety. This paper provides the component method to solve the secondary air system through the analysis between the component method and network method. And we carry out calculations for both steady and transient state problems by using the component method and network method toward series and parallel networks. The results agree well. Then, we couple the secondary air system with the main-flow components by component method to simulate the whole basin of aircraft engine. Finally, we analyze the change of performance and safety among the performance model, the whole engine model and the whole engine model which consider the cavity effect. Through the analysis of the results, we can predict that the whole engine model will provide help for the dynamic analysis of the secondary air system when the method develops maturely.

Key words: aircraft engine, secondary air system, the whole engine model, component method

1. Introduction

The secondary air system undertakes some important tasks, including cooling the high temperature components of engine, anti-icing, unloading, adjusting the axis-thrust, sealing, etc. So, the scientific design and accurate analysis of secondary air system will have impact on whether the engine meets the airworthiness requirements. The part 33 of the civil aviation airworthiness regulations includes some paragraphs related to the secondary air system. In order to analyze the influence of secondary air system and understand the transient characteristic of the whole engine, it is necessary to construct a model which includes the performance model and the secondary air system. On the other hand, when the aircraft engine operates in the transition state, some parts undertake the external load which has strong time-varying characteristics. They may become the main factors that cause engine failure. So, it is important to develop simulation technology of the whole engine model.

At present, secondary air system are modeled mainly by network method. The aircraft engine secondary air system is a special pipe system. The fluid network method developed in pipe system

Selection and peer-review under responsibility of Airworthiness Technologies Research Center, Beihang University/NLAA.
doi:10.1016/j.proeng.2014.09.085

simulation is the main simulation thought of aircraft engine secondary air system. The first thought of fluid network simulation can be traced back to 1936.Cross[1] firstly comes up with the system solution method to simulate the flow characteristics of fluid network and further to explore the simulation method of the steady fluid network. Kutz[2]et al analyzed the aircraft engine secondary air system based on the research results of the field of steady fluid network general simulation in 1994. On this basis, they put forward simulation method which involves most of the secondary air system components, which abstracts the secondary air system as the model composed of the chambers and pipes connection and represented by the corresponding physical relationship. Prasad[3]et al use the CFD software to research the secondary air system in 1997. They combine the CFD and network method to calculate the flow velocity of secondary air system of gas turbine engine in 2004[4]. These calculations involve in the real cooling air supplied to compressor disk, turbine disk cavity, bearing cooling, to guarantee the balance of axial thrust and prevent the gas ingress. Yannick Muller[5] used finite element software CalculiX to realize the coupling of network connected by node, chamber and the pressure loss with secondary air system thermal mechanical model in 2008. Shenping Hou, Zhi Tao[6-9] combined the fluid network method with unsteady simulation method to predict the unsteady characteristic of pressure, temperature, mass flow rate of secondary air system.

However, the calculation of secondary air system needs the boundary conditions provided by some performance models [10-12]. In analysis model of secondary air system, the dynamic change of its internal working state cannot provide timely feedback to the main-flow. In the performance model, the influence of the secondary air system embodied only in specific section of air bleeding and blending process in main-flow, which is a "black box" of performance simulation model. So, we need to couple the performance simulation model with the secondary air system model to analyze the aircraft engine. This paper will accept the component method to solve the secondary air system and verify the method feasibility through the simple cases. Then, we couple the performance simulation model with the secondary air system model. Considering the changes of performance and safety among the performance model, the whole engine model and the whole engine model which considers the cavity effect. From the results we can predict the change of the safety parameters in the transient state and see the importance of the whole engine model.

Nomenclature

p	pressure
p^*	total pressure
m	mass flow rate
Pnodei	the pressure of node i i=1,2,3.....
Welementi-j	the mass flow rate between the node i and node j i=1,2,3.....;j=1,2,3....
Tnodei-in	the inlet temperature of node i i=1,2,3.....
Tnodei-out	the outlet temperature of node i i=1,2,3.....
Wnodei-in	the inlet mass flow rate of node i i=1,2,3.....
Wnodei-out	the outlet mass flow rate of node i i=1,2,3.....
H	flight altitude
Ma	mach number
Ws	the mass flow rate of fluid
A_{nz}	the area of nozzle
F	thrust
SFC	specific fuel consumption
SM	surge margin
ENV	environment
HPT	high pressure turbine
LPT	low pressure turbine
HPC	high pressure compressor
NM	network method
CM	component method

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2. Component method of secondary air system

Now, the main simulation method of performance model and secondary air system model are respectively adopting component method and network method. They both employ the initial given parameters to iterative computations in the process of simulation solution, but the initial given parameters and selection mechanisms of balance equation have significant differences.

Performance simulation component method usually use the work parameters or performance parameters of each components as the initial trying to give parameters, computing the balance check residual based on the common working condition satisfied by every components and the selected engine control law. Further to establish the parameter correction matrix for iterative calculation of initial parameters. Component method should run the components in accordance with the flow direction.

Secondary air system network method regards the network as flow structure that are connected by nodes and elements. Solving the residual of flow rate through the nodes depends on trying to give the node pressure, then determining the pressure correction and solving the node pressure.

Due to different solution principles, the secondary air system model cannot be directly coupled with the main-flow component model. In addition, because complex components such as the compressor and turbine cannot establish the balance equations only by trying to give the node pressures. A preferred way is to take a unified component method to model the engine.

In order to make the component method have the universality of network method in dealing with the flow process of multiple branch crossing, realizing the aim to make the secondary air system as the system connected by components, we abstract the flow structure of multiple branch cross as a single or multiple combination of two kinds of most basic element models based on the main-flow bypass splitter and mixer model. The two basic elements are “shunt element” and “converge element” showed in Fig 1.

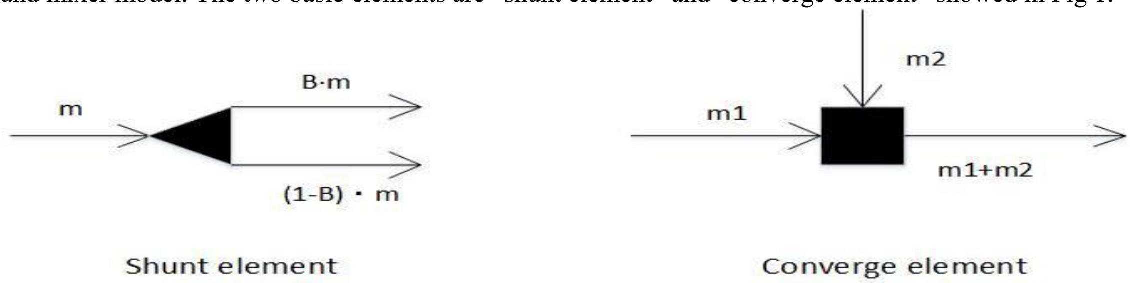

Fig. 1 shunt element and converge element

The shunt element is a component that divides one airflow into two airflows. Because the bleeding air of secondary air system and internal allocation proportion of each branch is a dynamic change in the process of engine practical work, we make the splitter proportion B of each shunt element as a initial variable that is solved iterate by balance equation.

The converge element is a component that mixes the two airflows into one airflow. This element generates the balance check equation based on the pressures of two airflows in the solution process of the whole engine system. This mainly considers two forms.

The first form is a converge model of static flow path which mainly describes the cooling air mixed with the main gas in main-flow static component. The generated balance check equation is pressure difference between total pressure of cooling air and static pressure of main-flow static component.

$$\varepsilon = p_2^* - p_1 \tag{1}$$

The second form is a converge model of cavity which describe the two cooling air branches mixed in the internal cavity of secondary air system. The generated balance check equation is pressure difference between the total pressures of two cooling air branches.

$$\varepsilon = p_2^* - p_1^* \tag{2}$$

The flow structure of secondary air system can connected by shunt element and converge element (the second). And the flow structure must satisfy the following equation.

$$I_{in} + I_s = I_{out} + I_c \tag{3}$$

Among this, I_{in} , I_{out} respectively express the number of flow path in inlet and outlet; I_s , I_c respectively express the number of shunt element and converge element. We utilize the equivalent substitution to connect the secondary air system with components. So, we can preliminary consider that the secondary air system modeled by component method is feasibility.

3. Comparison between two method

Both the calculation of network method and component method of secondary air system are based on continuity equation, momentum equation, energy equation and state equation. But the thinking of solution is different. Next, we can show that the component method can apply to solve the secondary air system through two simple cases.

3.1. case 1

Firstly, we compare the two methods through the steady and transient state toward a series network. The network is shown as Fig 2. The Fig 2(a) is a series network for calculation by network method; the Fig 2(b) is a series network for calculation by component method, which add a environment component. It begins from the environment component. The initial condition of Fig 2(a) is that the node pressure is 200000pa and temperature is 600K. The initial condition of Fig 2(b) is that the environment pressure is 200000pa and temperature is 600K. There we consider the cavity effect and carry on the calculation for steady and transient state.

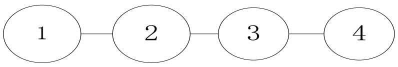

Fig 2(a) network method for series network

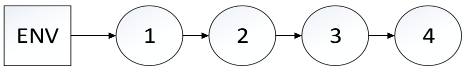

Fig 2(b) component method for series network

The control laws given in calculation of steady state are Pnode1=200000pa and Pnode4=100000pa. The results are shown as table 1 and table 2. The results are in agreement. The errors of pressure and flow rate are below 1E-6 and 1E-4. The temperatures of both networks are not change.

Table 1 the pressure comparison of steady state for series network

Pressure(Pa)	Pnode1	Pnode2	Pnode3	Pnode4
network method	200000	172918.4926	141056.7284	100000
component method	200000	172918.5096	141056.7593	99999.99998

Table 2 the flow rate comparison of steady state for series network

mass flow(kg/s)	Welement1-2	Welement2-3	Welement3-4
network method	0.18832162	0.188321591	0.188321476
component method	0.188322623	0.188322623	0.188322623

The control laws given in calculation of transient state are Pnode1=200000pa and Pnode4=f(t). The results are shown as Fig 3 to Fig 5. Because of the cavity effect, the temperature is no longer keeping constant. From the results, we can see that the curves of pressure, temperature and mass flow rate are coincident. The errors of these three parameters are in acceptable range. So, the results of transient state agree well.

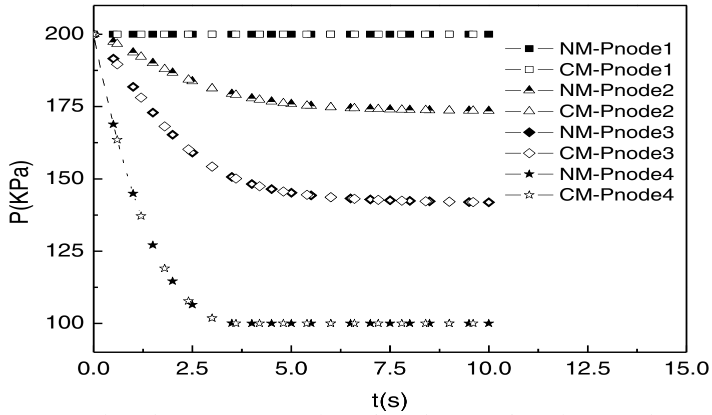

Fig. 3 the pressure comparison of transient state for series network

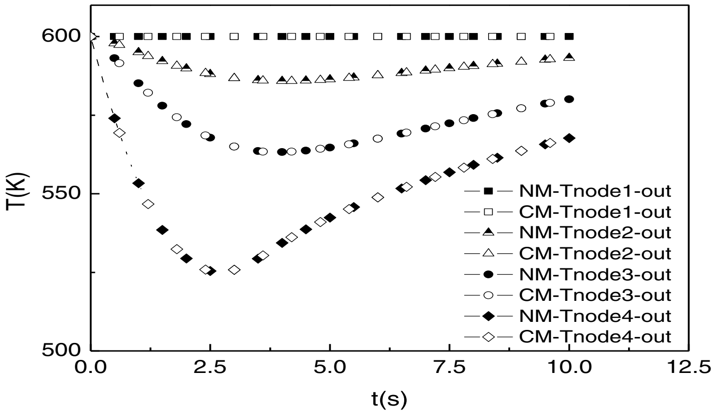

Fig. 4 the temperature comparison of transient state for series network

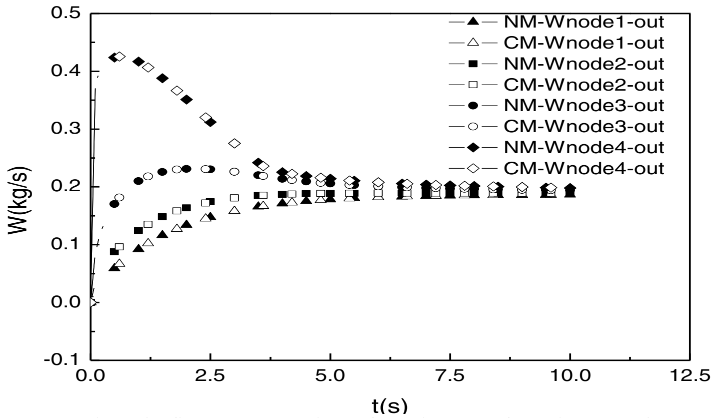

Fig. 5 the flow rate comparison of transient state for series network

3.2. Case 2

The above simple series network may not be enough to prove the equivalence of two methods, so we carry out the calculation of steady and transient state on a more complex parallel network. The network is shown as Fig 6. The Fig 6(a) is parallel network for calculation by network method; the Fig 6(b) is parallel network for calculation by component method, which add a environment component. The initial condition is the same as case 1.

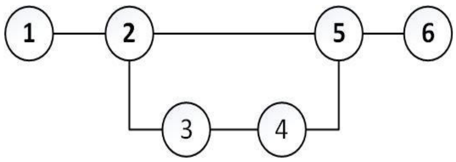

Fig. 6(a) network method for parallel network

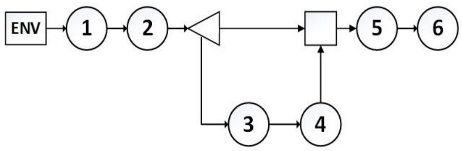

Fig. 6(b) component method for parallel network

The control laws given in calculation of steady state are Pnode1=200Kpa and Pnode6= 200Kpa. We compare the pressure and mass flow rate through each node in steady state between the two method. The results are shown as table 3 and table 4. From the results, we can see the error of pressure is below 3.1E-6; the error of mass flow rate is below 3.05E-5. The temperature is not change. The results are also in the acceptable range.

Table 3 the pressure comparison of steady state for parallel network

Pressure(Pa)	Pnode1	Pnode2	Pnode3	Pnode4	Pnode5	Pnode6
network method	200000	165733.6645	160528.3221	155125.6022	149516.8179	100000
component method	200000	165734.1114	160528.4754	155125.4547	149516.3554	100000

Table 4 the flow rate comparison of steady state for parallel network

mass flow (kg/s)	Welement1-2	Welement2-3	Welement2-5	Welement3-4	Welement4-5	Welement5-6
network method	0.210476087	0.076402455	0.134066191	0.076402387	0.076402373	0.210475976
component method	0.210474802	0.076404522	0.13407028	0.076404522	0.076404522	0.210474802

The control laws given in calculation of transient state are Pnode1=200000 and Pnode6=f(t). We compare the pressure, temperature and mass flow rate through each node in transient state between the two methods. The results are shown as Fig 7 to Fig 9. From the results, we can see that the curves of all nodes' pressure, temperature and mass flow rate are essentially coincident. And we can know that the errors of these three parameters are in acceptable range through the analysis and calculation. So, the results of transient state agree well.

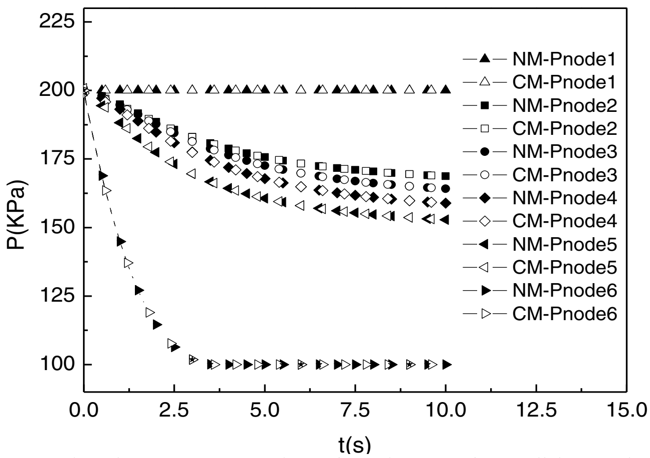

Fig.7 the pressure comparison of transient state for parallel network

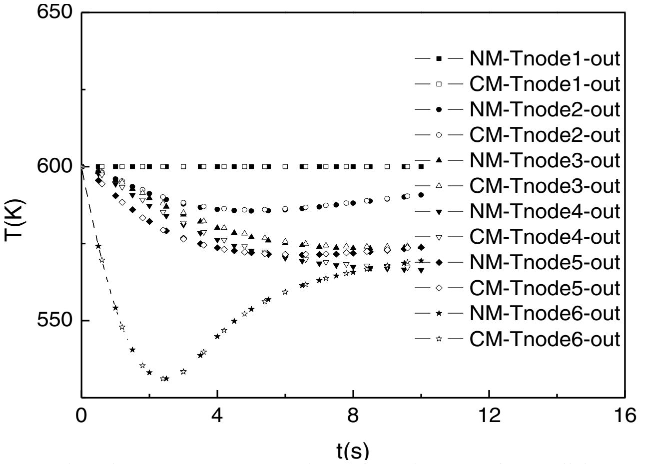

Fig.8 the temperature comparison of transient state for parallel network

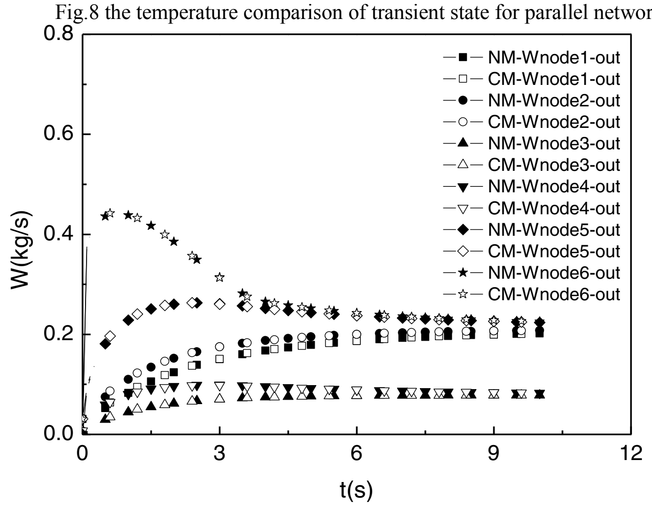

Fig.9 the mass flow rate comparison of transient state for parallel network

These tables show that the results agree well in both states from the above two cases. So, we can see that the secondary air system modeled by component method is feasibility. Thus, both the performance model and secondary air system model utilize component method to simulate. This method has significance in the simulation calculation of the engine integration. So, we can couple the performance model with the secondary air system to realize the simulation of the whole engine.

4. Engine model and analysis

The flow structure or design scale of secondary air system will affect the characteristic of engine. In order to satisfy some airworthiness requirements, we must reflect the design of secondary air system to the whole engine in timely. So, we use the components(holes, gaps, cavities, pre-nozzles, disk-axial clearance, labyrinth, etc) [13-15] to connect the shunt element and converge element to demonstrate the secondary air system. And we use the main-flow components of a turbofan engine to couple with the secondary air system by component method based on equivalence, establishing a complete model of aircraft engine internal flow, as shown in Fig 10.

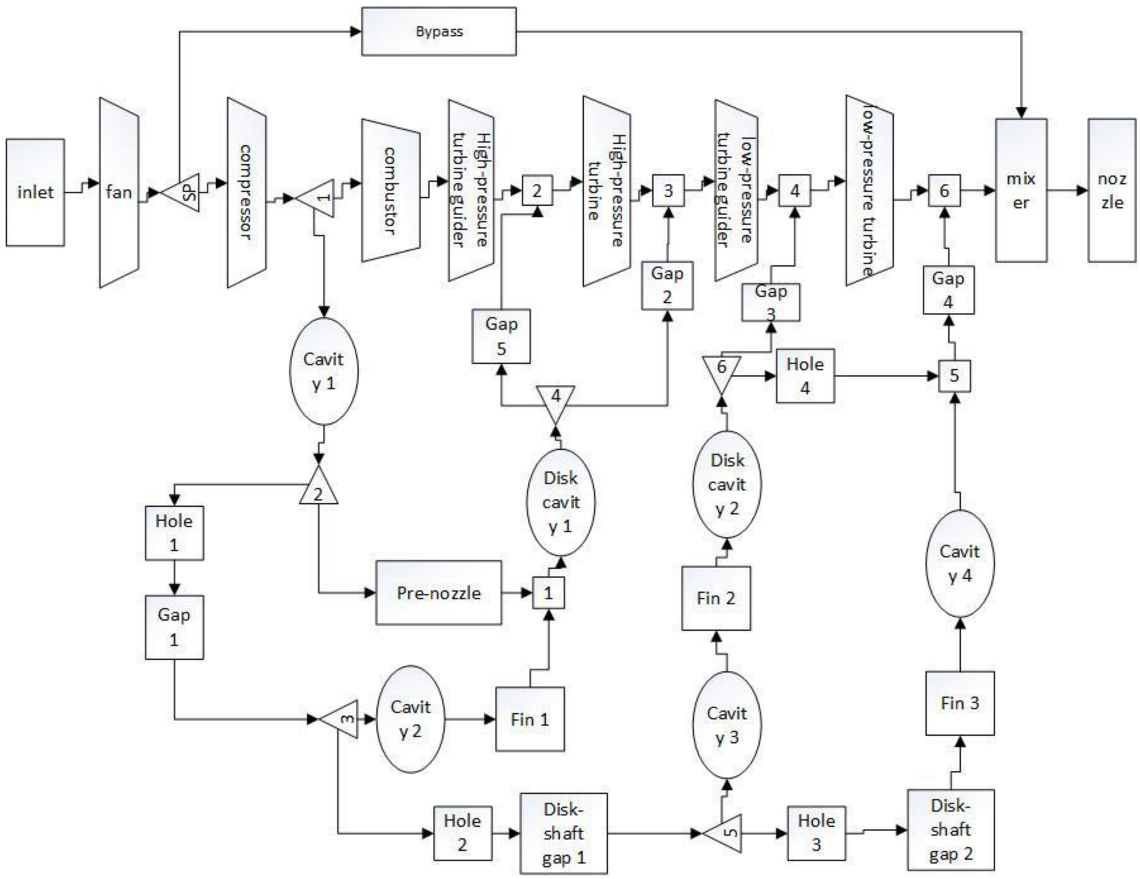

Fig. 10 Flow structure of the aero-engine

Here the secondary air system is assumed to interact only with the main-flow path without other aircraft bleeding, and the number of shunt element is equal to the number of converge element. Therefore, the balance equations are closed, without other constraints added. Here we make the comparison among the performance model, the whole engine model and the whole engine model which considers the cavity effect towards to the performance and safety in transient state. The engine accelerates from idle state to maximum state under the same initial condition and control law: H=0,Ma=0,Anz=0,Ws=f(t). The results are shown as Fig 11 to Fig 15.

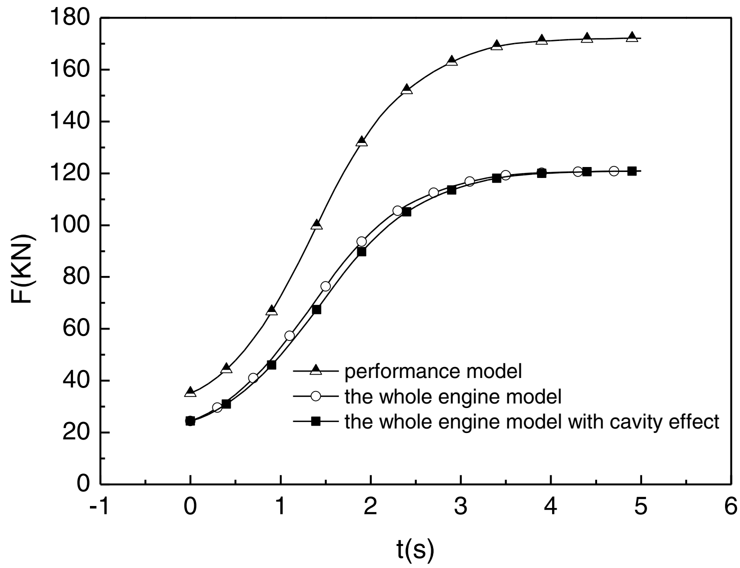

Fig. 11 thrust changes under three circumstances

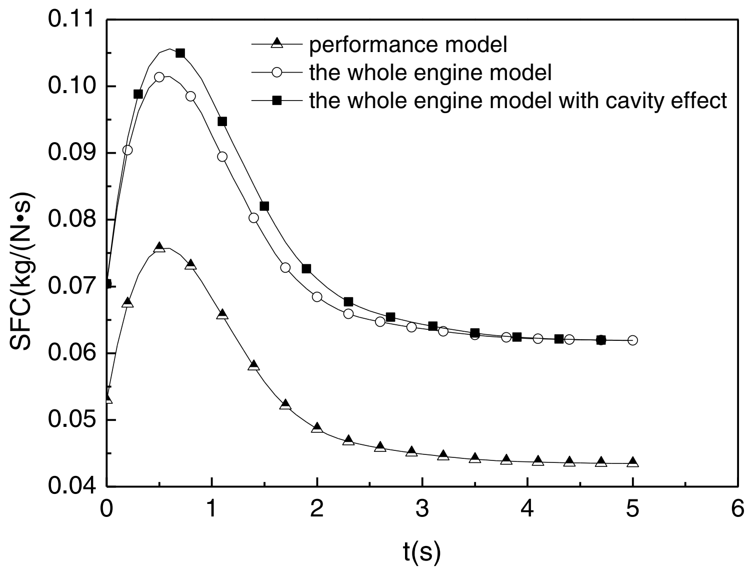

Fig. 12 SFC changes under three circumstances

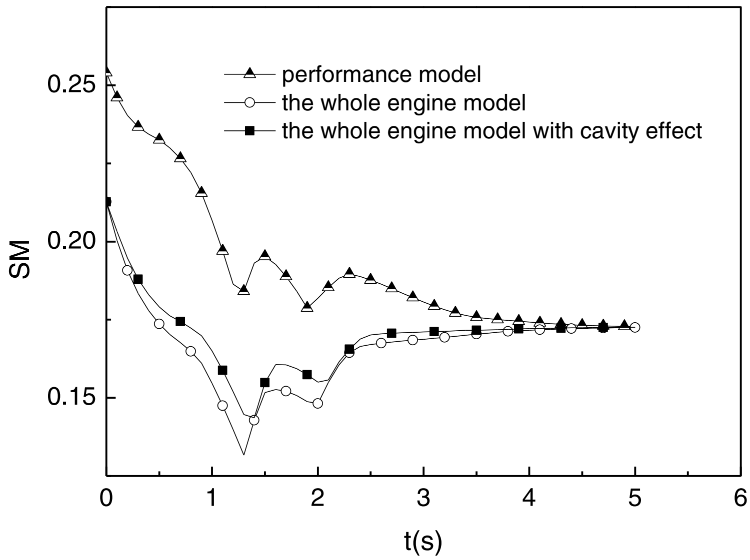

Fig. 13 the SM of fan changes under three circumstances

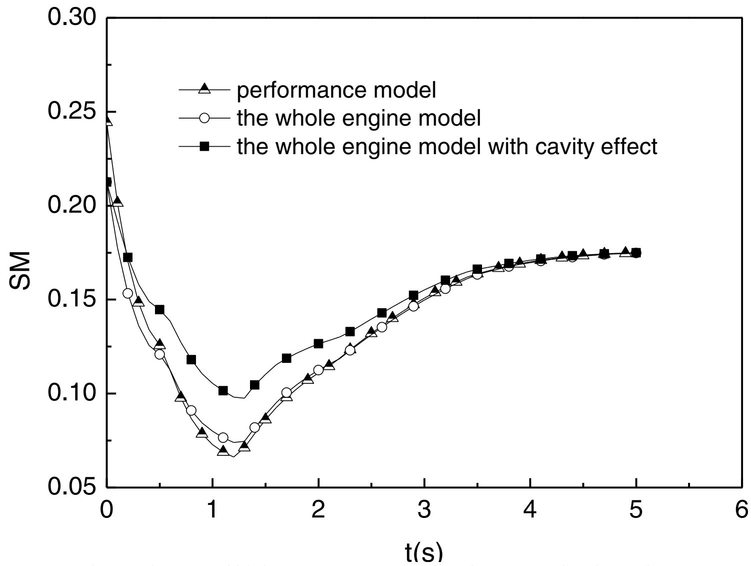

Fig. 14 the SM of high-pressure compressor changes under three circumstances

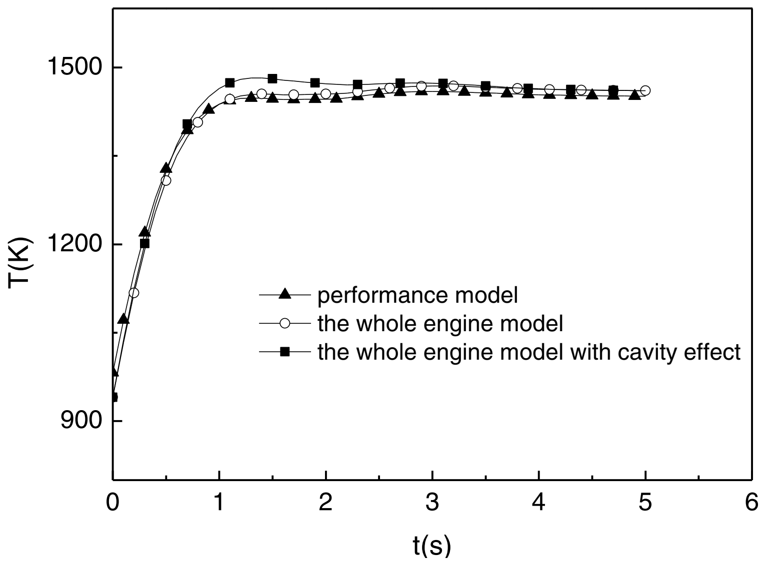

Fig. 15 inlet temperature of high-pressure turbine changes under three circumstances

The Fig 11 and Fig 12 show the thrust and SFC changes under the three different circumstances. We can see that the whole engine model will make the thrust decrease and SFC increase. The cavity effect makes the performance further decrease.

The Fig 13 shows the SM of fan changes under three different circumstances. We can see that the SM of fan of the whole engine model obvious decreases before 4 seconds. When we consider the cavity effect, the SM of fan increases slightly in the middle process. In Fig 14, we can see that the SM of HPC of the whole engine model increases slightly in the middle process. The cavity effect makes the SM of HPC further increase before 4 seconds. In Fig 15, we can see that the inlet temperature of HPT increases slightly in the whole engine model. And the cavity effect makes the temperature further increase especially in the 1-2 seconds.

Firstly, we can see that the change trend of each parameter is similar. So, it is considered that we can explore the transient characteristic of engine by the whole engine model simulated by component method. Then, when we add the secondary air system to the performance model, the performance will change tremendous in the transient state, and the safety end value is approximately equal. But the safety change obviously in the middle process of the transient state. The SM of fan and the inlet temperature of HPT will be close to the safety boundary. And, the cavity effect will influence the performance and safety more or less. So, this change of safety may cause the airworthiness decrease or engine failure. Due to the change as shown by the analysis, we must couple the secondary air system with the performance model to analyze the transient safety of engine and optimize its design parameters.

5. Conclusion

This paper provides a method to construct the whole basin simulation of aero engine. Firstly, we make the secondary air system components connect through the shunt element and the converge element. Then we carry out calculations for both steady and transient state problems by using the component method and network method towards series and parallel networks. The error of the results is in the acceptable range. So we can think that the component method is comparative with the network method for secondary air system. Finally, we construct the whole engine model based on the component method of secondary air system.

Based on the whole engine model, we make the comparison among the performance model, the whole engine model and the whole engine model which considers the cavity effect towards the safety and performance in transient state. The results show that the whole engine model simulated by component method is suitable for observing the safety of engine influenced by the dynamic characteristic of secondary air system. We can clearly see the problem provided by the couple. The whole engine model makes the SM of fan and the inlet temperature of HPT close to the safety boundary with comparison to the performance model, especially in the process of transient state. This change may cause the engine failure, therefore, it is important to research the change of engine safety parameters in transient state.

In summery, it is necessary to establish the whole engine model to understand the inside of engine. We will utilize the whole engine model to analyze the functions of the secondary air system and explore its transient characteristic by the completed whole engine model. In addition, we can analyze the working characteristic of secondary air system in the whole flight envelop.

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